

Improving the Processes of Land-Atmosphere Interaction in CCSM 2.0 at High Resolution

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This project contributes to the DOE climate-modeling program by building on a previously funded effort but includes some new foci, afforded by the opportunity to utilize areas of expertise at Georgia Tech modeling.

For land surface process, we have seen in the last decade many more component models developed than are needed for use with Earth System Models, and most have not been produced with the generality needed for the CCSM. This surfeit of land models has suggested the need for one or more codes so well done in terms of physics and code, that it would become much easier for anyone wanting to begin work contributing to land surface GCM research to start their research with this code rather than building yet another land model from scratch. Although ideally such a model should include all the best features of existing models, such was deemed impractical, so the PI initiated the concept of a “Common Land Model Prototype” that would use the best features of his BATS and with Gordon Bonan’s LSM, currently part of the CCSM model at NCAR, and the Chinese IAP code, and in so doing, demonstrate the feasibility of a wider community effort. As summarized further in subsequent sections, many collaborators working together individually contributed extensively and provided major elements of what has become accepted as the next-generation land sub-model for the NCAR CCSM.

The CLM as currently formulated provides a state-of-the-art treatment of the biophysical coupling needed for CCSM. At the summer 2000 CCSM workshop, the land working group decided to provide a more comprehensive land package that integrated the CLM treatment of biophysics with parameterizations of the coupling to terrestrial biogeochemical and atmospheric chemical processes important for the overall Earth System model. All these processes are strongly dependent on the land model representation of vegetation and soils, and the underlying boundary data sets that quantify the geographically and seasonally varying model parameters. The PI is using NASA EOS funding to develop and improve the boundary data sets to be used by CCSM as a component of CCSM. The present proposal focuses on developing computational aspects of the land-atmosphere interactions that will place as extreme demands on the underlying data sets as is feasible with current computational resources. In doing so, it is expected to provide the land framework for other future DOE climate modeling studies.

Land boundary data can now be inferred from satellite remote sensing at 1 km resolution. Because of the considerable importance of land climate, the DOE climate modeling

program will want to explore ways to integrate climate models over land at the highest possible resolution. We are developing that theme through integrating land sub-models at finer grids than the atmosphere models and the atmosphere model at highest resolution achievable. In addition, we are working to develop and improve land model aspects that are especially sensitive to treating land at a high resolution. We are emphasizing developing linkages to the modeling connections between land processes and atmospheric chemical composition.

The present proposal has 4 general objectives, each of which leads to a series of tasks we propose to accomplish:

- Complete the development of the land sub-mesh representation as an element of the next generation CCSM land model and evolved from CLM.
- Continue implementation of the latest versions of CCM (i.e. atmospheric component of CCSM 2.0) at resolutions normally attained only by mesoscale models. (Resolutions down to 0.5 degrees are now achievable.)
- Further develop and validate components of the Community Land Model component of CCSM.
- Improve and develop the CCSM interface between land processes and atmospheric chemistry.

Common Land Model

The primary implementer of this new code has been Y.J. Dai. This activity has since entrained the active participation of a substantial number of other land-surface modelers, and quite a few of these have, like Dai, contributed as much or more to the effort than the PI has been able to. Especially notable have been efforts of Z.L. Yang and X. Zeng at Arizona, who respectively thoroughly reworked and documented soil layering codes initially developed by the PI, and provided much for the needed organizational focus and a good formulation for the M.O. surface layer physics; and P. Houser at GSFC, who added FORTRAN 90 wrappers to the code to allow the physics code to be done for GCM code the same as off line code and without need to keep track of array structures, and Mohammad Shaikh who developed and carried out prototype simulations with CLM in CCM3 as well as developing code to run CLM with the Lin-Rood finite volume code, for use by DAO scientists. The land working group of the CCSM activity, chaired by Bonan and Houser, has identified the CLM as the next-generation land model for CCSM. With that step has come the most recent and impressive contributions of Mariana Vertenstein, Boville's programmer at NCAR, who, working with Bonan and Oleson, has provided an extensive rework of the code that not only provides the next generation interface to NCAR's CCSM models, but also makes the code highly readable and modular.

Further development of fine mesh representation of land in the context of CCSM/CLM

This objective includes completion of the sub-mesh scaling rules to be used, and inclusion of the code as an optional or possibly standard element of the CCSM land package. Present codes are operational for a half a degree sub-mesh representation of LSM and BATS in T42 version of CCM3.0. These will be reworked with the codes and coding styles of the latest version at NCAR of the CLM land surface code as part of the CCSM 2.0, the next-generation community climate system model, expected to be

publicly released later this year. We will continue to carry out simulations and testing with the atmosphere coupling to land model for the 17-year period of AMIP2 SST data set.

The land software system at NCAR currently in support of LSM and also to be used with CLM provides boundary data sets, in principle at any model resolution, by remapping from a high-resolution archive. However, the high-resolution archive developed by Bonan's group is tabulated at 0.5 degrees; this resolution is not sufficiently fine to support either the land fine-mesh representations that we are developing or the under 0.5 degree atmospheric model simulations that are proposed here. In addition, the current formulation of elementary land surfaces in terms of non-vegetated areas and plant functional types should be further improved. We propose to develop new high-resolution data sets, based on our work with NASA satellite land data, to provide input data at a much higher resolution and in other ways to enhance the flexibility and versatility of the data.

The underlying high-resolution boundary data represents land cover as vegetation, wetland, ice sheets, urban, or lakes, and subdivides the vegetation according to plant functional types. This data is currently used to define the fractions of these types for the LSM and CLM tiles underlying a CCM grid-square. Our fine mesh approach will be reformulated to support both a subdivision of these fractional types among the sub-mesh geographically located tiles and sub-tiles within each sub-mesh grid point. In this way, the model can support together mixture types of land cover and individual plant functional types.

Run atmospheric component of CCSM 2.0 over AMIP2 period at the resolution of a mesoscale model

Our previous attempt at this task with a preliminary version of Williamson's semi-Lagrangian model showed both interesting conclusions and some difficulties that should be overcome to obtain publication quality results. Completing the simulations depended on an allocation from the UCAR CSL system that was not fully utilized because much of the period was used in the preliminary preparation of model boundary conditions at the higher resolutions.

We uncovered difficulties in the AMIP2 SSTs in the Gulf of California too late for them to be fixed, and we were only able to complete a few years at the T-191 and T-239 resolutions. It was also not practical to publish results with an undocumented atmospheric model.

Our previous experience allows us to specify much more rapidly the input data and output fields required for thorough analysis of the land atmosphere coupling. The imminent release of well-documented code for CCSM 2.0 provides an excellent framework for repeating and improving the previous calculation – that is, 17-year AMIP2 simulations at resolutions from about 1.0 degree to finer than 0.5 degree to determine the improvement with finer resolution in continental regional climates, of various model fields, especially precipitation and temperature patterns. The previous experience showed

little improvement in summer and tropical precipitation patterns, possibly an artifact of CCM3s oversimplified scheme for moist convection.

The new model includes a superior convection scheme provided by Randall's group at CSU. We will determine whether or not with this convective scheme, the large-scale patterns of convective precipitation improve with finer resolution. Our analysis will emphasize simulation of the Pan American monsoon systems in conjunction with CLIVAR and GEWEX programs, but we will also explore how well are the Asian monsoon systems simulated, especially over China in collaboration with Chinese colleagues, and over India in collaboration with INDOEX follow-on work of Ramanathan's C4 program (the PI is chair of the SAC for C4).

Develop and validate components of land processes in CCM for use with CCSM

Further evaluation of CLM against observations will contribute to enhancing its robustness and the confidence that the community can place in its performance, especially in the context of time scales. Evaluation against available data on soil moisture is an especially important task that we propose to support under the present proposal.

Since soil moisture has a memory considerably longer than that of most of the atmospheric processes, a climatic anomaly may persist through processes dependent on soil moisture. Accurate prediction of soil moisture is consequently important for CCSM simulations. The soil transport processes can carry climatic signals both upward and downward. Evaporation and transpiration are the primary mechanisms through which soil moisture influences meteorological phenomena, in the upward direction of the two-way land-atmosphere interaction.

Wu will build on her PhD analyses that compared observational data with LSM by evaluating CLM simulations of the key land surface prognostic variables, such as soil moisture, runoff and evapotranspiration against observations such as from FIFE. She will further investigate, evaluate, and describe physically two-way coupling between the soil moisture and the atmosphere through sensitivity experiments with CLM. These will be conducted to examine the impacts of various potential controlling factors: (i) the atmospheric forcing at the upper boundary (P/EP), (ii) the root sink term and how it helps determine the partitioning between transpiration and runoff, (iii) the soil texture, determining the thermal and hydraulic properties of soil, and (iv) perturbations in the level of groundwater for a dry upper surface, and hence of the upward climate signals from the soil moisture to evapotranspiration.

Analysis of 16-year observations from ICN (Illinois Climate Network) has provided a description of the soil moisture profile variability phase shift, fluctuation damping and persistence increasing with soil depth occur. This variability as a function of soil depth is linked to the time scales of the atmosphere, to a small extent, the climate spectra. The 10-layer fine resolution CLM provides us an opportunity to explore the mechanisms underlying the variability. Whether or not CCSM can reproduce this variability should be a good test of the adequacy of CLM treatment of soil hydrology.

We also propose that Dai build on his work as the major architect of the CLM next generation land model by further developing various parameterizations of CLM for use with CCSM. Details of the current CLM treatment of stomatal functioning are somewhat controversial and require further improvement. The total stomatal resistance and photosynthesis are integrated from a separate calculation for sunlit and shaded leaves under the same foliage temperature, hence ignoring the several degree temperature differences between sunlit leaves and shaded leaves. Preliminary simulations based on a separate calculation of temperature for sunlit and shaded leaves show such differences of the temperatures, and consequent modifications of the integrated stomatal resistance and photosynthesis. Dai will provide a robust treatment of the separate temperature calculations for sunlit and shaded leaves.

There are currently three alternative stomatal resistance schemes that might be used with CLM: (i) Dickinson's interactive canopy model, (ii) Bonan's LSM photosynthesis and stomatal resistance scheme, and (iii) Henderson-Sellers' SiB2 scheme. Dai will identify the optimum features of each of these schemes and other recent similar treatments and on this basis provide an improved photosynthesis and stomatal resistance scheme.

Dai has found with off-line simulations that details of the vertical profile of soil texture can have a substantial impact on the simulations of soil water and evapotranspiration. Soil texture occurs in nature with large heterogeneity both regionally and vertically. The current version of CLM uses a global soil texture data set from IGBP-DIS that provides vertical profiles. Off-line and on-line simulations will be carried out to establish the sensitivity of soil moisture and evapotranspiration to the specification of the vertical profile of soil texture.

Dai will also work toward improving other CLM treatments that are problematical such as those of land-ice and wetlands.

Interactions between Land Processes and Atmospheric Chemistry

Because atmospheric gases and aerosols affect the transfer of both terrestrial and solar radiation, chemical processes in the atmosphere are part of the earth's climate system and thus need to be incorporated into the CCSM as indeed is being done through various existing efforts, e.g. sulfate aerosol chemistry has been incorporated into CCM3 (Rasch et al. [2000a,b], Barth et al. [2000], and Kiehl et al. [2000]). However, earth system models must address another important aspect of atmospheric chemistry: namely, how the land surface acts as a source and sink for atmospheric species and in turn is affected by the chemical composition of the atmosphere.

We propose here to address two aspects of this issue: (i) exploring and refining the algorithms within the CCSM/CLM modeling system that simulate the effect of radiative impact of aerosols either directly on surface energy and water budget processes and hence boundary layer dynamics or indirectly through modification of stomatal functioning; and (ii) developing algorithms within the CLM to simulate the land-atmosphere exchange of trace gases and aerosols (e.g., sources of biogenic VOC, NH_3 and dry deposition of besides these, aerosols, and O_3). This proposed research will not

attempt to compete with or replicate current efforts at NCAR and elsewhere to represent atmospheric chemical processes within the CCSM, but would instead complement these efforts by focusing on land/atmospheric-chemistry interactions. This area of the proposal will be the responsibility of the Chameides, Yu, and Liu, who have been working with several other models, e.g. RegGCM, to explore the coupling between atmospheric chemistry and land processes. We are proposing to refocus this research toward contributing to the advancement of this aspect of CCSM.

Current research on the coupling between aerosols and climate is largely focused on the radiative forcing caused by aerosols as a result of the so-called direct, indirect, and pseudo-direct effects (Charlson et al. 1992; Schwartz, 1996; Hansen et al., 1997; Haywood and Boucher, 2000; Rosenfeld, 2000; Ackerman et al. 2000; Jacobson, 2001). Perturbations of solar radiation by aerosols not only manifest themselves as changes in radiative fluxes at the top of the atmosphere but also as even larger changes in the radiative flux at the land surface. Aerosols also modify the precipitation received at the land surface. These impacts provide consequent modification of latent and sensible heat fluxes, atmospheric boundary layer dynamics, fog frequency, soil moisture and temperature, soil respiration (e.g., Liu et al. 2001, Yu, 2000); and perturbations in both the total Photosynthetically Active Radiation (PAR) and its diffuse fraction, in turn affecting stomatal controls of evapotranspiration, photosynthesis and rates of carbon storage by the biosphere (e.g., Chameides et al. 1999; Gu et al. 2001).

Initially we will use the 1-dimensional version of the CCM (the SCCM) coupled with CLM to explore and refine the model's simulation of land-process/boundary layer responses to prescribed aerosol optical depths and single scattering albedos (i.e., as determined through aerosol absorption by black carbon and mineral aerosols). Aerosol loading will be chosen to represent regions of the globe where aerosol concentrations are most significant (e.g., regions of China influenced industrial emissions and/or mineral aerosols, the southeastern United States), and will be based on aerosol distributions derived from MODIS data (King et al. 1999), surface measurements (for example, from NASA's AERONET and USDA UV-B monitoring networks for the U.S. and from the Chinese Academy of Meteorological Sciences [CAMS] solar-radiation monitoring network for China [see Chameides et al. 1999 and Zhou et al. 1998]), and/or global model simulations from the CCM as they become available. The simulations will determine the potential climatic significance of the various interactions discussed above (and thus establish the need for their inclusion in the CCSM), as well as the sensitivity to uncertainties in the relevant parameterizations. Connections to shallow convection and fog will be addressed following Liu et al. [1999].

Boundary layer and land surface responses will be examined in the context of the diurnal cycle. We will examine approaches to improve the realism of the specification of the diffuse component of the solar radiation, e.g. we will also consider the effect of using more sophisticated models for calculating the diffuse fraction (e.g., Madronich, 1993; Fu et al. 1997). To evaluate the overall model performance, we will compare model-predicted soil-temperature and moisture responses to aerosols to those observed at USDA and CAMS monitoring sites.

Following the SCCM analyses we will explore global-scale responses of land processes and boundary layer dynamics to aerosols by carrying out high-resolution CCM/CLM simulations. We anticipate two 1-year simulations: one with anthropogenic aerosols and the other without. To the extent possible, the simulation of the emission, production, transport, and removal of aerosols will be accomplished using algorithms that have been developed for by NCAR scientists for the CCM, thus maintaining connectivity with other elements of the CCSM development activity. (WLC has had discussions with P. Rasch of NCAR on the establishment of the appropriate collaborative relationships to facilitate this part of the proposed project.)

The exchange of gases between the atmosphere and terrestrial biosphere both determine in part aerosol properties and concentrations and affect on the oxidizing capacity of the atmosphere and thus on the concentration of important greenhouse gases (e.g., methane). The CLM, as its LSM predecessor, already simulates most of the processes and parameters needed to drive algorithms that can calculate gas exchange rates. We propose to develop modules within the CLM to do this. Our initial efforts in this area will focus on the emissions of biogenic VOC (e.g., isoprene) and the dry deposition of O_3 . We will also work toward using formulations of soil nitrogen cycling supported under other grants to parameterization of the emissions of NH_3 from the land surface. Such requires data-bases for various agricultural practices such as fertilization and feedlots. Bonan at NCAR has already done some preliminary calculations of biogenic VOC emissions with LSM. Such can be calculated using the approach of Guenther et al. (1995) but requires more detailed specification of plant functional types than required for most applications of CLM. The other required parameters, biomass/LAI, leaf temperatures, and PAR, are readily available. O_3 dry deposition can be parameterized in terms of a dry deposition velocity as described in Wamsley and Wesley (1996) and Chameides (1989) and requires specification of various boundary layer properties, surface roughness (i.e., ecosystem type), LAI, and stomatal resistance. Once the algorithms have been completed and fully evaluated, we will begin development of parameterizations for dealing with the effects of sub-grid heterogeneity in land cover on these parameterizations.